SYNOPSIS OF TIMING MEASUREMENT TECHNIQUES USED IN TELECOMMUNICATIONS

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Abstract

Historically, Maximum Time Interval Error (MTIE) and Maximum Relative Time Interval Error (MRTIE) have been the main measurement techniques used to characterize timing performance in telecommunications networks. Recently, a new measurement technique, Time Variance (TVAR) has gained acceptance in the North American (ANSI) standards body. TVAR was developed in concurrence with NIST to address certain inadequacies in the MTIE approach. This paper describes the advantages and disadvantages of each of these approaches. Real measurement examples are presented to illustrate the critical issues in actual telecommunication applications. Finally, a new MTIE measurement is proposed (ZTIE) that complements TVAR. Together, TVAR and ZTIE provide a very good characterization of network timing.

1. MEASUREMENT CRITERIA

A good starting point in evaluating timing analysis techniques is to set objectives of what constitutes a good approach. A good measurement technique is one that efficiently extracts the useful information from the timing signal in a repeatable and cost effective manner. The usefulness of the information extracted is closely tied to the use of a good practical model. Historically, the model used to described timing signals in non telecommunications applications is based on a simple decomposition of the signal into two components:

- Systematic components (Phase Offset, Frequency Offset, and Frequency Drift)
- Stochastic Power Law noise components, $S_x(f) = \sum_{n=0}^{4} \alpha_n f^{-n}$ (white pm, flicker pm, white fm, flicker fm, random walk fm).

This model permits the characterization of a complex timing signal with a handful of parameters. The premise that this model can be extended to telecommunication synchronization distribution applications is reasonable. Conceptually, one can treat a distributed network of clocks as a single composite super clock. The dominant sources of noise and bias may be different, but the resulting timing signal will still be characterized by this model. This approach has recently been adopted by ANSI committee T1X1 . Extensive field phase data has been analyzed using TVAR (described

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **DEC 1992**	2. REPORT TYPE	3. DATES COVERED **00-00-1992 to 00-00-1992**
4. TITLE AND SUBTITLE **Synopsis of Timing Measurement Techniques Used in Telecommunications**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Symmetricom Inc,Telecom Solutions,2300 Orchard Parkway,San Jose,CA,95131-1017**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADA267301. 24th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, McLean, VA, 1-3 Dec 1992**		
14. ABSTRACT **see report**		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**13**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

later) as the measurement tool to extract the key parameters of the model [ANSI T1X1.3/91-074]. The dominant noise types found in the network are white PM, flicker PM and white FM.

The fact that more divergent noise processes (such as random walk FM) are not significant indicated that the network is reasonable traceable in frequency to the primary reference sources.

1.1 Dual Role of Measurement/Modeling Approach

One role that the measurement approach fills is the need to extract the timing model parameters. The critical issues in this role are:

- Does the measurement approach extract the essential parameters ?
- Does it use the data efficiently (fast convergence of parameter estimates)?
- Is it practical to compute?
- Is it robust to practical measurement anomalies (glitches, gaps etc.)?

A key role that the modeling approach fulfills is the need for timing specifications and standards. The critical issues in this role are:

1. Is the parameter set compete (does the model allow for timing signals that meet the parameters but have undesirable attributes)?
    - Is the parameter set excessive (does the model over–constrain the design of the network or the elements)?
    - Does the model permit networking of elements and subnetworks (can one interconnect clocks and/or subnetworks and determine overall performance)?

2. MEASUREMENT TOOL DESCRIPTION

Three measurement approaches are compared in the paper:

1. M[R]TIE (Maximum [Relative] Time Interval Error) ,
2. TVAR (Time Variance),
3. ZTIE (Z–transformed processed Time Interval Error)

2. 1 M[R]TIE

M[R]TIE is the established measurement approach for telecommunications. The bracketed [R] (Relative) is used to distinguish the reference timing signal. When the term is used with the [R] (MRTIE) the reference timing signal is the input to a timing element and the signal under test is the network element output. When no [R] is used (MTIE), the reference is considered to be ideal (practically a primary reference source). For simplicity, MTIE will be used as a general description of both measurements.

MTIE is fairly straightforward to describe. For a given observation interval (usually termed S) the phase error between two timing signals is observed. The peak to peak phase (delay) variation of

the error signal is the MTIE for that sample interval. The observation interval can be considered as window function. As the window slides through the phase error signal, the next sample of MTIE is calculated. The MTIE for the overall phase data set is the maximum of all the individual MTIE samples. For full overlapping processing of MTIE, there is a greater than linear growth in computation resulting from the need to search for minimums and maximums.

MTIE appears to be a useful approach when considering conventional network controlled slip rates. The maximum peak to peak delay variation impressed on a frame alignment (slip) buffer is directly related to MTIE . However, the controlled slip mechanism is a function not only of peak to peak buffer movement, but also of the type of movement. Monotonic movement will result in a slip rate governed by the frame size (typically 125 microseconds) and the rate of phase movement (frequency offset). But, cyclical movement results in a slip rate governed by the hysteresis in the buffer control (which can be as small as 18 microseconds). MTIE provides little information regarding the underlying model controlling the phase motion in the buffer. The basic attributes of MTIE are:

1. Monotonically increasing with increasing observation intervals.
2. Suppresses Phase bias; asymptotically converges to frequency or drift bias for long observation intervals.
3. Captures peak information regarding delta time variation.

2.2 TVAR

TVAR (Time Variation) is a new term to some, but it is based on the well established Modified Allan Variance (MVAR). TVAR can be viewed as a filtering operation applied to the raw phase error signal. The filtering operation is diagramed in Figure 1. The following notation is used:

1. f is normalized in units of T^{-1} where;
2. T is the observation interval (averaging interval),
3. $T = n \bullet T_0$ where T_0 is the sampling period, and n is the number of samples in the observation interval.

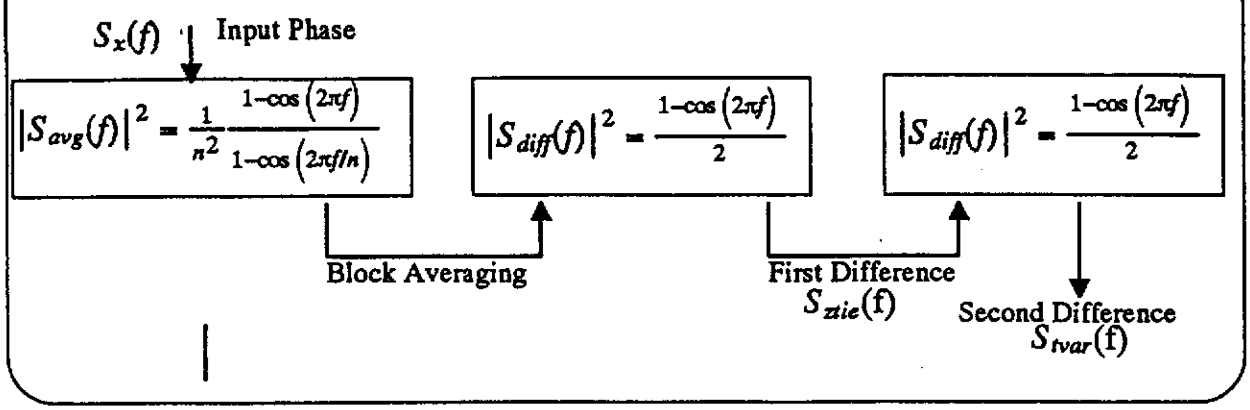
The TVAR filter can be viewed as consisting of three sections:

1. Block Averaging,
2. First Difference, and
3. Second Difference.

The block averaging provides a T dependent low pass filter characteristic. The transfer function of the block averaging function is illustrated in Figure 2.

The block averaging function has the characteristic main lobe with a zero at 1/T. The main function of the block averager is to provide a Tau dependent low pass filter to suppress jitter and provide for discrimination between flicker PM and white PM. As will be shown in section 3 this low pass function is critical in telecommunications as timing signals can be dominated by these higher frequency noise components.

Figure 1: TVAR and ZTIE processing (Frequency Domain)



The next operation is the first difference. The first difference transfer function is shown in Figure 2. The main purpose of the difference operator is to provide suppression of the f^n divergent power law noise processes. The first difference provides 20 dB per decade suppression . This is adequate to ensure a stationary noise power process for input phase noise with white noise FM as the most divergent noise (which is the expected case for traceable timing signals). The first difference operation also suppresses phase bias. In TVAR processing the difference operator is applied twice yielding an overall second difference. This ensures stationarity for noise processes up to random walk FM which is the most divergent noise expected in general oscillator applications. The second difference also suppresses frequency bias. Since frequency bias is a critical parameter, TVAR needs to be complemented with another measurement in describing telecommunication timing signals.

The composite TVAR transfer function is shown in Figure 2. It is essentially a bandpass filter with a center frequency and bandwidth controlled by the averaging time T. To complete the calculation of TVAR the variance of the filtered output signal is calculated for each observation interval (T). A close analogy can be drawn to an FFT based spectral analysis. The bandpass filter function can be viewed as a window function centered at a specific frequency (approx $T/2$). Normally TVAR is calculated in a geometric series of $2^{-n}T_0^{-1}$ frequency bins. An FFT is based on a arithmetic series of 2^n frequency points. In an FFT the bandwidth of the window function is fixed. In TVAR analysis the bandwidth is proportional to the frequency bin. TVAR is tailored to being an efficient method to extract broadband power noise processes. FFTs are in general better suited for analyzing frequency over a smaller dynamic range.

2.3 ZTIE

The basic concept behind ZTIE is that a peak power measure is needed to complement TVAR. ZTIE is one possible approach to providing a bandpass measure of peak power. ZTIE measures the peak power using a bandpass filter controlled by the averaging time T. Figure 1 shows that ZTIE is calculated from the output of the first difference function used in calculating TVAR. The reason that the first difference output was selected over the second difference is that it does not

suppress the frequency bias term of the model. The importance of this will be seen in the examples in the next section. ZTIE is calculated by simply measuring the peak output of the first difference operator. The peak information is critical to providing bounds to the model parameters. As the examples will show, it is risky to assume that the peak to rms ratio is gaussian in telecommunication networks.

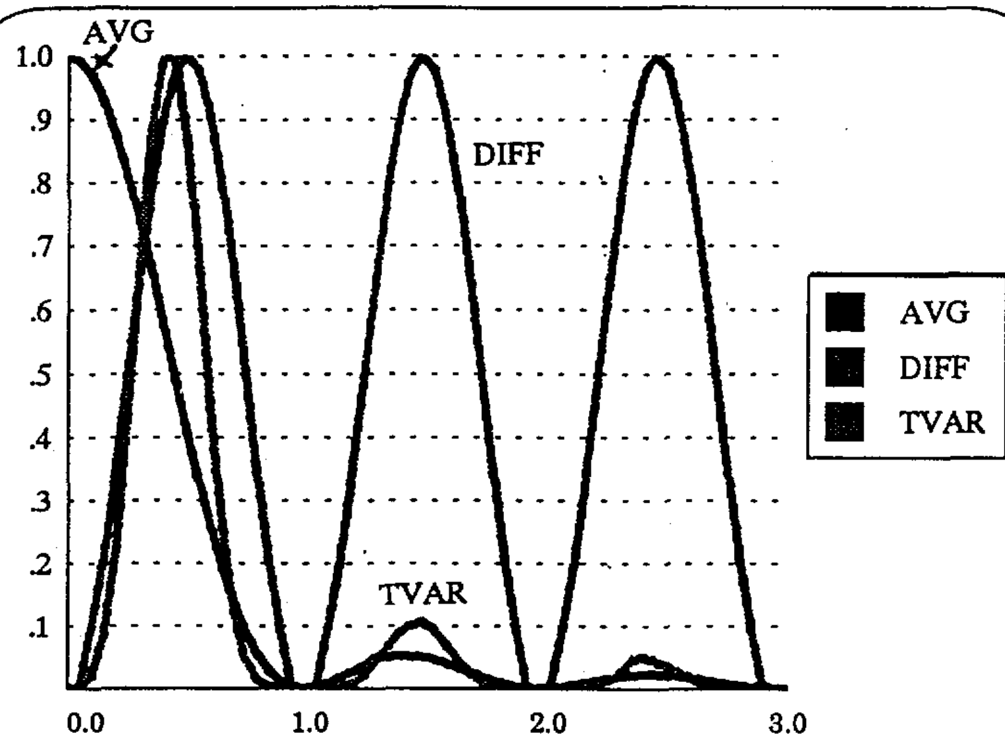


Figure 2: TVAR and ZTIE Transfer Function Components in units of $1/T$.

3. MEASUREMENT EXAMPLES

This section provides a selection of measurement examples to illustrate the key attributes of each measurement method. The measurement examples were generated using a simulation approach.

3.1 Power Law Noise Examples

Figures 3a, 3b and 3c illustrate the measurement behavior for White PM, Flicker PM and White FM respectively. Each simulation was run for 86,400 sample points.

Figure 3a shows the results for a gaussian white PM input signal. In addition to the TVAR, ZTIE and MTIE results, an asymptote showing the -1/2 expected slope is plotted. The TVAR result shows the expected behavior:

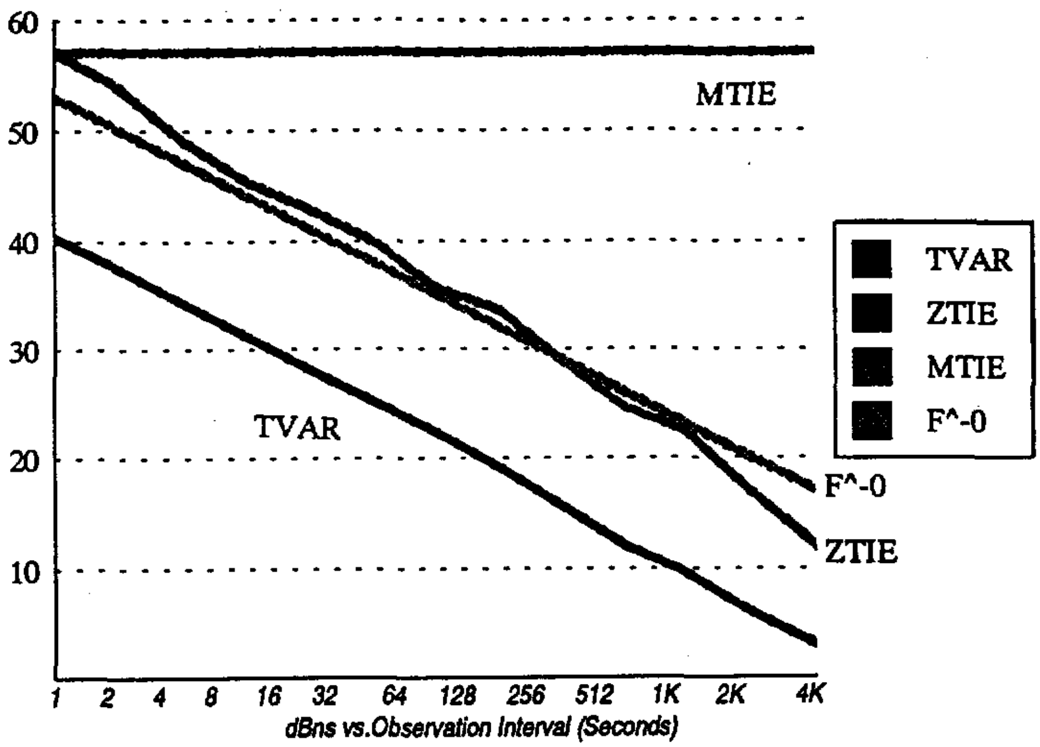


Figure 3a: Simulation results white PM case.

1. At T_0 the TVAR (actually the root TVAR) value 40dBns (100 ns) equals the noise level of the input jitter.
2. The -1/2 slope shows the root law reduction in rms error associated with averaging .

The ZTIE result shows the same trend as the TVAR data. The slight droop at longer averaging times is explained by the reduction of independent peak power measurements (fewer measurements reduce the likelihood of finding a point on the tail of the distribution). The TVAR curve is running about 14 dB above the ZTIE curve showing a well behaved peak to rms ratio.

The MTIE result highlights the inadequacy of MTIE in extracting useful data for white PM noise. The MTIE shows a slight increase for longer observation intervals. Naturally, since the bandwidth of the measurement increases with observation interval there is increasing probability of finding a higher noise peak.

Figure 3b shows the results for Flicker PM. The TVAR results show the flicker PM noise floor as a horizontal asymptote. This is a very practical feature of TVAR. The flicker PM floor represents the best time error calibration that can be realized for a given timing signal. This is important when we consider issues like phase error during rearrangement of clock timing inputs. A clock cannot resolve phase better than the flicker PM noise floor of the reference input.

ZTIE shows a similar behavior as with white PM. The peak to rms ratio is well behaved. The

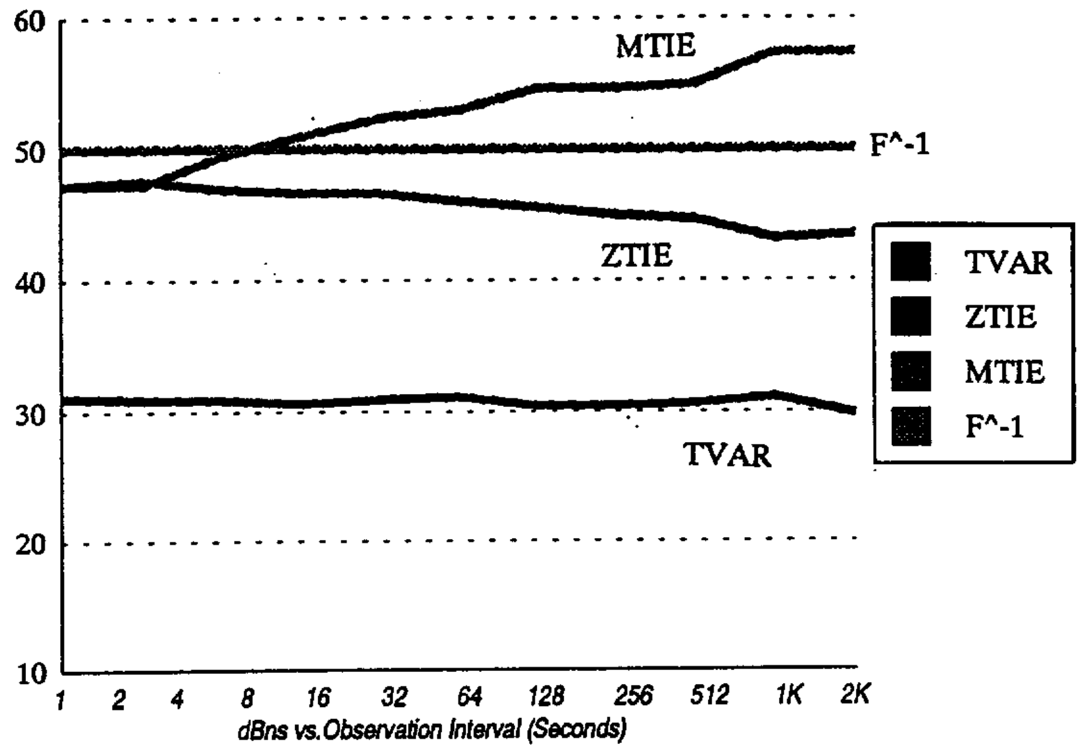


Figure 3b: Simulation results flicker PM case.

peak information is very useful in this case as it bounds the peak phase error achievable during rearrangement (approx 220 ns in this case).

MTIE behaves much better with a divergent noise process input. However, it still shows a 10 dB positive skew for longer observation intervals.

With white FM all three measures show the $+1/2$ slope divergence of the timing error expected (Figure 3c). Note that ZTIE and MTIE converge for white noise FM. ZTIE has been designed to converge with MTIE for longer observation intervals where either white FM or frequency bias dominate.

3.2 Telecommunication Network Examples

The examples in this section are constructed to illustrate issues related to the telecommunications network.

3.2.1 Transient Glitch

In measuring actual network timing data there is the practical issue of managing transients. The transient may be part of the measurement system, disruption in the transport path or a clock anomaly. Regardless, a good measurement approach should not completely mask transients or let

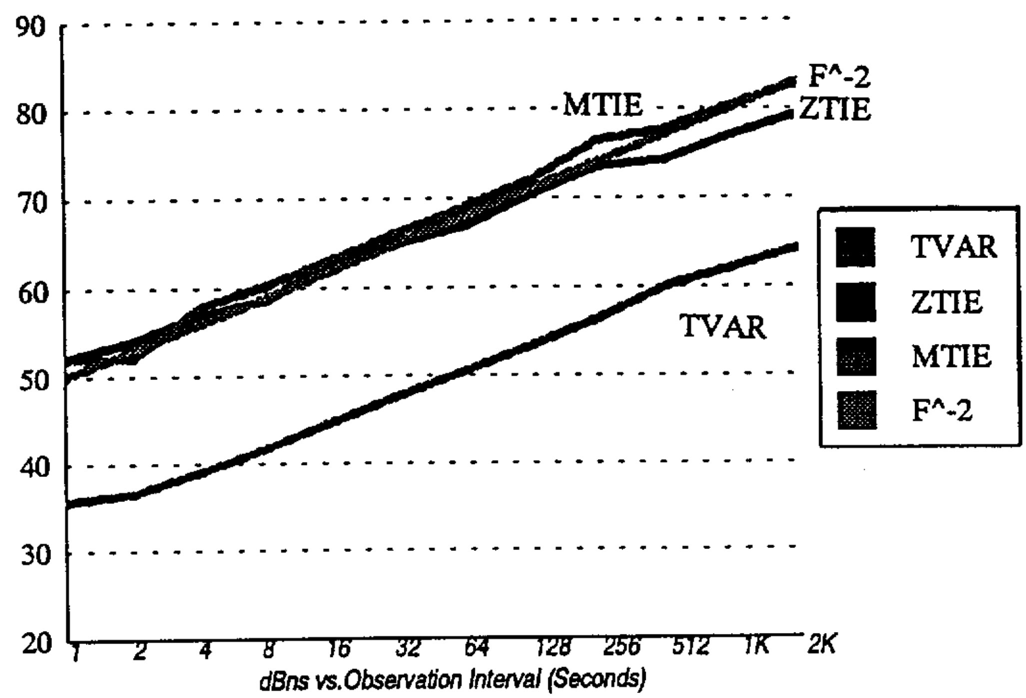


Figure 3c: Simulation results white FM case.

transients mask steady state performance. Figure 4 shows the response of the three measurement approaches to a simple phase impulse event.

TVAR is plotted for two data collection intervals (one hour and one day). Since TVAR is an rms power estimator, it tends to remove transient impulses (which are finite energy zero average power). Thus, TVAR needs to be complemented with a peak estimator to capture transient information.

ZTIE shows an interesting response to the impulse. The total peak level of the impulse is shown at T_0 (10,000 ns). The power level is then linearly suppressed for longer observation intervals.

MTIE is extremely sensitive to transients. A single transient can completely mask out the underlying noise model for the timing signal. This is a serious weakness in the application of MTIE to actual network timing analysis.

3.2.2 Jitter plus Frequency Offset

Figure 5 illustrates an example of a realistic network timing signal.

The timing signal is constructed with nominally 1 UI of peak to peak timing jitter. This level of jitter is well within worse case network limits (5 UI), and is a reasonable bound for expected network transport jitter over the existing plesiochronous digital network. The frequency bias (1×10^{-10})

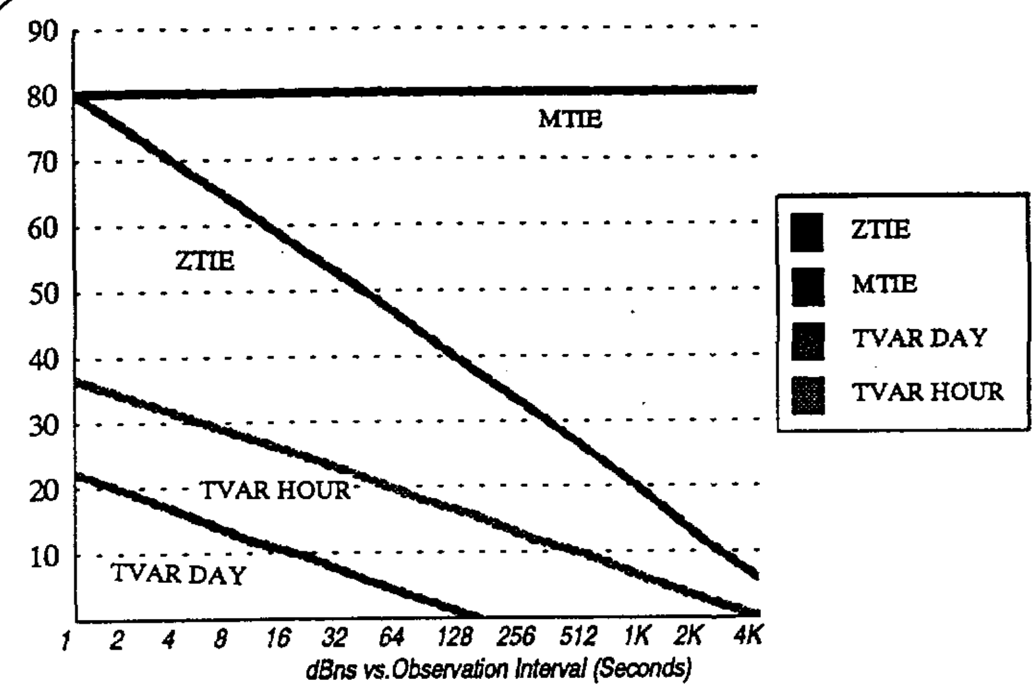


Figure 4: Simulation results Impulse Response Case.

represents a timing signal that has impaired frequency traceability to the primary reference source (the next example suggests one of a number of mechanisms for this to occur).

TVAR effectively suppresses the frequency offset and correctly reports the underlying white PM transport jitter. ZTIE is very effective in showing both the short term peak jitter noise component and the long term frequency bias. MTIE again is inadequate to show the true underlying noise process.

This is a good example to consider from the point of view of timing specifications and standards. One can consider how well this measurement results would function as network timing interface standards. A key question is how well one can calibrate the frequency of slave clock to a network timing reference? The ability to calibrate directly impacts slip performance during reference outage conditions. For sake of illustration let us consider a clock with a 128 second averaging algorithm. At 128 seconds the MTIE value is 488 ns. Since the MTIE mask provides no insight on the underlying noise process, one can't assume white PM. In fact, the only safe assumption is that this 488 ns phase instability cannot be effectively filtered. This leads to frequency calibration error bound of 3.8×10^{-9}. In contrast, at 128 seconds ZTIE has a value of 30 ns. A mask based on ZTIE would constrain the worse case frequency calibration to 2.4×10^{-10} (over an order of magnitude tighter).

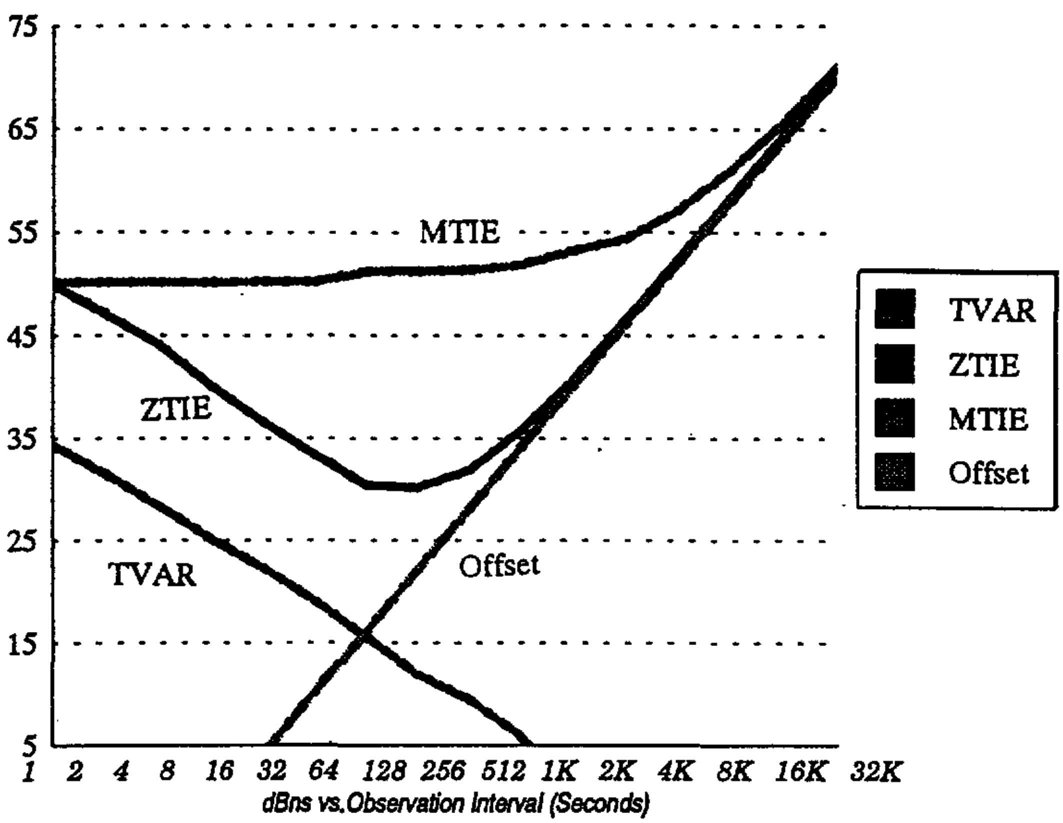


Figure 5: Simulation results jitter plus 1E-10 Frequency Offset

3.2.3 Network Timing Signal (Stress Condition)

Figure 6 shows the measurement results for a network timing signal under stress conditions.

CCITT G.812 defines a clock under stress conditions. One stress condition is frequent transient disruption on the reference transport. For constructing the simulation for network stress one reference disruption per hour was used. This level of disruption is within the maintenance performance action limits for network transport. The disruption activity will lead to reference rearrangement transients. The following model for reference rearrangement was simulated:

1. The maximum total phase movement at the clock output in response to a transient is assumed to be either plus or minus 1 UI (488ns). This is within the current maximum of 1,000 ns allowed for in network timing standards.
2. The direction of the phase step is assumed to be a bias with positive steps occurring with a 75% probability. Bias errors can result from numerous hardware and software sources in a clock.

In addition to the hourly reference disruptions, white PM was added to the timing signal to simulate network transport jitter (the jitter distribution was assumed to uniform with a 1 UI peak to peak magnitude.

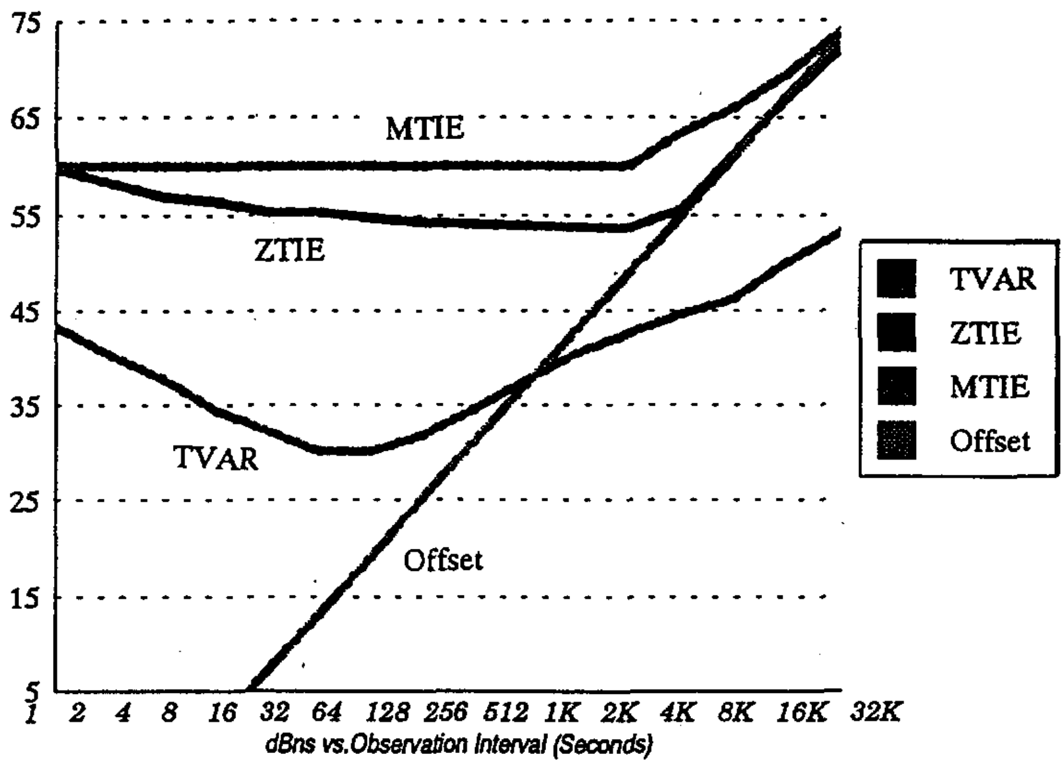


Figure 6: Simulation results Network Stress Conditions

The TVAR result clearly shows two dominant noise processes. The white PM transport jitter dominates for short observation intervals, and the white FM associated with the reference rearrangements dominates for longer observation intervals.

The ZTIE result shows that timing signal error distribution is definitely non-gaussian. The random walk in phase is quantized in 1 UI steps. These phase steps manifest themselves as impulsive noise. ZTIE complements TVAR by showing that the peak error is dominated by non-filterable transient steps rather than the underlying white FM noise process. The TVAR results suggest that the best time calibration error is 32 ns. ZTIE shows the true achievable timing calibration performance is actually limited to 500 ns.

MTIE performs fairly well for this constructed example because the phase walking process dominates. However, ZTIE still provides a correct estimate of the underlying frequency offset (which in this case is 6×10^{-11}), about ten times faster than MTIE.

4. SUMMARY

Measurement and modeling are closely related. The use of the power law model in conjunction with TVAR as a measurement technique provides a very effective platform to characterize network timing performance. However, TVAR is inadequate for establishing network timing specifications

and standards as it fails to extract important information concerning peak noise power, frequency biases and transients. MTIE has been shown to be inadequate as measurement tool for a variety of practical network scenarios. ZTIE is proposed as one measure of peak power. It complements TVAR by providing information on peak noise power, frequency bias and transient activity. It is designed to converge with MTIE for longer observation intervals. The use of both TVAR and a bandlimited peak power measurement like ZTIE in telecommunication applications is increasingly critical as new synchronous optical transport (SONET and SDH) require more accurate and tighter specification of network timing.

QUESTIONS AND ANSWERS

G. Winkler, USNO: A single characterization is sufficient. What I wonder is what actually is wrong in using structure functions. That has been proposed some 15 years ago by Lindsey, as I remember; probably David Allan will remember that. This discussion entered, at that time, to use a different set of differencing in measures of these differences. The maximum value of the RMS values and so on.

Comment: I think from the scientific community there is a much better parameter set that could be obtained. From where the telecommunication's community is, I think this introduction of TBAR by itself, which is very simple to cause a major conniption. One of the things I mentioned that ZTIE behaves just like MTIE does on the long term. That was one of the attributes that, I knew, I had to have a connection there, so it's a very simplistic measurement is trying to take the most logical step. So it is a practical issue as to why this step is the way they are currently. That is a good point.

R. Brown, Bellcore: Just as a side to that, the telecommunication community has adopted using time variance or time deviation as an additional parameter to MTIE. We are very indebted to the National Institute and Standards and Technology: Dave Allan, Mark Weiss for their help in that. We are not time and frequency people, we kind of dabble in it, we are getting a feel for it. We needed some help with that and greatly appreciate the efforts of NIST.